Stability and Transition Analysis for Reentry tool, STAR

Final Technical Report
March 2005

Submitted by

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REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-05-

0506

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for i
and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this bu
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1. REPORT DATE *(DD-MM-YYYY)* 032005	2. REPORT TYPE Final Report	3. DATES COVERED *(From - To)* 1 Jun 2004 - 31 Dec 2004

4. TITLE AND SUBTITLE Stability and Transition Analysis for Reentry tool, STAR	5a. CONTRACT NUMBER
	5b. GRANT NUMBER FA9550-04-1-0407
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S) Dr. Helen L. Reed	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Department of Mechanical and Aerospace Engineering Ira A. Fulton School of Engineering Arizona State University Tempe AZ 85287-6106	8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) USAF/AFRL AFOSR 875 North Randolph Street Arlington VA 22203	10. SPONSOR/MONITOR'S ACRONYM(S) AFOSR
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution Statement A. Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

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contractors supported under the DARPA FALCON program in the development and test of Common Aero Vehicle (CAV)
maneuvering reentry configurations. Under this effort, state-of-the-art computational tools developed for hypersonic boundary
layer stability research will be integrated into a user-friendly package (the Stability and Transition Analysis for Reentry tool,
STAR). STAR will be based on Parabolized Stability Equation (PSE) solvers, with additional modules to account for crossflow,
transient growth, and roughness effects. Previous flight and ground test data will be analyzed for validation and calibration of the
new tool, and stability and transition on actual contractor-provided CAV configurations will be analyzed computationally in
concert with ground tests of the same configurations.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
U	U	U	UU	6	19b. TELEPHONE NUMBER *(Include area code)*

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Stability and Transition Analysis for Reentry tool, STAR

Summary

The effort is primarily to accelerate delivery of an improved stability and transition analysis tool. The initial goal is to aid contractors supported under the DARPA FALCON program in the development and test of Common Aero Vehicle (CAV) maneuvering reentry configurations. Under this effort, state-of-the-art computational tools developed for hypersonic boundary layer stability research will be integrated into a user-friendly package (the Stability and Transition Analysis for Reentry tool, STAR). STAR will be based on Parabolized Stability Equation (PSE) solvers, with additional modules to account for crossflow, transient growth, and roughness effects. Previous flight and ground test data will be analyzed for validation and calibration of the new tool, and stability and transition on actual contractor-provided CAV configurations will be analyzed computationally in concert with ground tests of the same configurations.

The goal is to deliver source code and documentation that is to be made available at no charge to prospective users, as directed by the Department of Defense. The code will run on Linux clusters running MPI. Additional documentation will report the details of the test cases used for calibration and validation. STAR is to become a government-furnished code like POST, HYCOM, or CMA, which is available from a government source and continuously improved in terms of accuracy and range of applicability.

Detailed Technical Approach and Progress to Date

Laminar-turbulent transition is critical to gliding hypersonic reentry vehicles and hypersonic airbreathing cruise vehicles, such as those presently being developed under the DARPA FALCON program. However, no ground-test facility can reliably evaluate transition, as none combine the low noise levels, high Mach numbers, high transition Reynolds numbers, and high enthalpy levels that are observed in flight. Reliable test and evaluation of transition-sensitive designs will require development of a new transition-prediction tool. This tool must extrapolate from new and existing ground experiments and existing flight data, to obtain reliable results for new designs in flight, without extensive flight testing. A reliable tool must be based on the actual physical mechanisms that lead to transition; such a tool now appears feasible due to continuing improvements in computational capabilities.

Therefore, the STAR program proposes to develop a mechanism-based transition prediction tool for hypersonic flows, to be first used for the gliding reentry vehicles associated with FALCON. This tool will be developed, calibrated, and validated using existing and new experimental data from ground and flight tests, both unclassified and classified. A comprehensive effort of this type has never been attempted before, as previous attempts to compare to flight data were carried out in the 1970's, when mechanism-based transition simulations were not feasible for flight vehicles.

The ASU team consisted of Professor Helen Reed and graduate student Peter Brady (US citizen) who began to exercise the prediction tool for unclassified test cases. To this end, they worked with Professor Graham Candler and Dr. Heath Johnson at the University of Minnesota. Candler

and Heath are the developers of the prediction tool. Reed and Brady initially used the STABL code – a limited-access linear PSE code with a 2-D basic state – provided by Candler and Johnson.

Purdue provided expertise in the physics and the experimental database, for both ground and flight tests, and provided unclassified test cases to Reed and Brady. Schneider also aided in the interpretation of the experiments and the analysis of the computational results. In addition, Purdue will be providing new experimental data in the Boeing/AFOSR Mach-6 Quiet Tunnel (presently running with conventional noise levels except at low pressures). These new experiments focus on blunt cones at angle of attack and will include roughness effects.

Reed and Brady computed the flow over a sharp cone at 0 AOA as an initial test case for comparison with the experiments of Schneider. The sharp cone has a 7-deg half-angle, is 16.3 inches in length, and has a base diameter of 4 inches. The cone surface temperature is 300K and the freestream Mach number is 5.8. The basic state was completed and verified, and the stability calculations were underway.

ASU also advised the Minnesota team in the development of mechanism-based transition-estimation modules based on the *nonlinear* parabolized stability equations, and started to evaluate the computational tool for unclassified test cases. ASU also advised on modeling crossflow-instability physics.

Reed is also part of the Rapid Assessment Tool for Transition Prediction (RATTraP) team with Lockheed Ft Worth, developing transition tools geared for high-altitude, long-range vehicles for the Air Force. The kick-off meeting for this complementary activity occurred Oct. 26, 2004, at Lockheed Martin in Ft Worth, Texas.

The work will continue at Texas A&M University.

Schedule and Milestones for STAR Program

20 April 2004 Kickoff meeting at WPAFB

29 Sept 2004 Kickoff meeting with FALCON contractor Lockheed Martin in Palmdale, CA

Every-other-weekly telecoms occur among each of whole STAR Team, Flight Test Team, Experiments Team, and Tool Development Team.

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EDUCATION
Ph.D.	Engineering Mechanics	Virginia Polytechnic Institute & State Univ	Dec 1981
M.S.	Engineering Mechanics	Virginia Polytechnic Institute & State Univ	June 1980
A.B.	Mathematics	Goucher College	May 1977

EXPERIENCE
Dec 2004–present	Professor and Head, Aerospace Engineering, TAMU
July 2003-Aug 2004	Vice Chair for Graduate Programs, MAE, Arizona State Univ
July 1992-Dec 2004	Professor, Mechanical & Aerospace Engineering, ASU
Aug 1993-Aug 1996	Director, Aerospace Research Center, ASU
Sept 1991-June 1992	Assoc Prof, Institute Fluid Sciences, Tohoku Univ., Sendai, Japan
Aug 1985-June 1992	Associate Professor, Mechanical & Aerospace Engineering, ASU
Sept 1982-Aug 1985	Assistant Professor, Mechanical Engineering, Stanford University
June 1977-Dec 1981	Aerospace Technologist, NASA/Langley Research Center
Summer 1976	Mathematics Aid, NASA/Langley Research Center

PROFESSIONAL ACTIVITIES
Scientific and Professional Societies
Fellow, American Society of Mechanical Engineers (ASME)
Fellow, American Physical Society (APS)
Associate Fellow, American Institute of Aeronautics and Astronautics (AIAA)
Member, AMSAT (Radio Amateur Satellite Corporation)

Service to the Profession
Member, Scientific Advisory Board, *National Institute of Aerospace (NIA)*, 2003 – present.
Member, *AIAA Fluid Dynamics Technical Committee*, 2002-2006.
Deputy Co-Chair, *National Space Grant Student Satellite Program Steering*, Jan. 2002 – present.
Member, *U.S. National Transition Study Group*, 1984-mid 1990s, 2004 - present.
Member, Amer Physical Society Div of Fluid Dynamics Nominating Committee, 2003 – present.
Associate Editor, *AIAA Journal*, 2003-2004.
Chair, USRA Space Technology Council, Jan. 1999-2003
Commissioner, Arizona Space Commission (Arizona-Governor-appointed), Jan. 2000 – 04
NASA Blueprint for 21st Century Aviation Workshop, Warrenton, VA, July 24-26, 2001
NASA Aerospace Technology Advisory Committee, NASA Headquarters (HQ), 2000-01
Small Aircraft Transportation System, FAA REDAC /NASA ASTAC Subcommittee, 2000-01
2050 AeroSpace Vision, FAA REDAC/NASA ASTAC. Fed Transportation Adv Group, 2000-01
NASA Aero-Space Technology Advisory Committee (ASTAC), NASA HQ, 1998-2000
NASA Independent Assessment Team for New Millennium Deep Space 3, 1997-98
NASA Aeronautics and Space Transportation Technology Adv Committee, NASA HQ, 1997-98
NASA Federal Laboratory Review Task Force, NASA Adv Council, Sept. 1994-March 1995

NASA Aeronautics Advisory Committee (AAC), NASA HQ, Dec. 1994-96
NATO/AGARD Fluid Dynamics Panel, 1995-98
NASA Aeronautics Advisory Committee Task Force on University Strategy, 1995-97
Executive Committee, Amer Physical Society/Div of Fluid Dynamics (APS/DFD), 1996-99
Board of Directors, Society of Engineering Science, 1993-95
NSF Presidential Young Investigator Workshop, US Engrg, Math, Science Ed for 2010, 1990
National Academy of Sciences/National Research Council Aerodynamics Panel, 1990-92
Associate Editor, Annual Review of Fluid Mechanics, 1986-2000
Originator, Gallery of Fluid Motions, APS/DFD, since 1983

Current Fields of Interest
Boundary-layer transition and flow control, hypersonic flow, micro-/nano-satellite design, satellite constellations and formation flying, interplanetary missions, micropropulsion, uninhabited aerial vehicles. Recent work includes:
- Design of swept laminar-flow wings for DARPA Quiet Supersonic Platform that involves ASU-invented discrete-periodic-roughness laminar-flow technology
- Design of swept laminar-flow wings for HiLDA/SensorCraft program using aforementioned ASU-developed distributed-roughness laminar-flow technology
- Stability/transition of hypersonic chemically reacting boundary layers on reentry vehicles (STAR)
- Stability/transition of hypersonic boundary layers on HyperX-like forebodies including compression corners
- Unstructured-grid solutions to design aerodynamic control of micro aerial vehicles

SCHOLARLY AND CREATIVE CONTRIBUTIONS
Relevant Publications - Journal and Society Papers
"Design Considerations of Advanced Supercritical Low Drag Suction Airfoils," Pfenninger, Reed, Dagenhart, *Viscous Flow Drag Reduction, AIAA Progress Astronautics and Aeronautics Series*, 72, 1980.

"Flow over Plates w Suction through Porous Strips," Nayfeh, Reed, Ragab, *AIAA J.* 20, 5, 1982.

"Numerical-Perturbation Technique for Stability of Flat-Plate Boundary Layers with Suction," Reed, Nayfeh, *AIAA J.*, 24, 2, 1986.

"Effect of Suction and Weak Mass Injection on Boundary-Layer Transition," Saric, Reed, *AIAA J.*, 24, 3, 1986.

"Stability of 3-D Boundary Layers," H. Reed, W. Saric, *ARFM*, 21, 235, Jan. 1989.

"Effects of Streamwise Vortices on Transition in Plane Channel," Singer, Reed, Ferziger, *Phys Fluids A*, 1, 12, 1989.

"Stability 3-D Supersonic Boundary Layers," Balakumar, Reed, *Phys Fluids A*, 3, 4, 617, 1991.

"Transition Correlations in 3-D Boundary Layers," Reed, Haynes, *AIAA J.*, 32, 923, 1994.

"Boundary Layer Receptivity to Free-stream Vorticity," Buter, Reed, *Physics of Fluids*, 6, 10, 3368, 1994.

"Linear Disturbances in Hypersonic, Chemically Reacting Shock Layers," Stuckert, Reed, *AIAA J.*, 32, 7 1994.

"Linear Stability Applied to Boundary Layers," Reed, Saric, Arnal, *ARFM*, 28, 1996.

"Drag Prediction and Transition in Hypersonic Flow," Reed, Kimmel, Schneider, Arnal, *(Invited) AIAA-97-1818.*

"CFD Validation Issues Transition Modelling," Reed, Haynes, Saric, *AIAA J.*, 36,5,742-52,1998.

"Boundary-Layer Receptivity to Freestream Disturbances and Its Role in Transition," Saric, White, Reed, *(Invited) AIAA-99-3788*, 1999.

"Simulation of Swept-Wing Vortices using Nonlinear Parabolized Stability Equations," Haynes, Reed, *JFM*, 305, 325-349, Feb. 2000.

"DNS Leading Edge Receptivity to Sound," Fuciarelli, Reed, Lyttle, *AIAA J.*,38,7,1159-65,2000.

"Validation of Parabolized Stability Equations for 3-D Boundary Layers," Reed, Saric, *Invited Paper, ASME Paper No. FEDSM2000-11345*, 2000.

"Adaptive, Unstructured Meshes for Navier Stokes Equations for Low-Chord-Reynolds Numbers," Monttinen, Shortridge, Latek, Reed, Saric, *AIAA Progress Astronautics and Aeronautics*, 195:60-80, 2001.

"Stability of High-Speed Flows", Reed, Saric, Lyttle, Asada, *Invited paper, AIAA-2001-2700.*

"Supersonic LFC on Swept Wings Using Distributed Roughness," Saric, Reed, *AIAA-2002-0147.*

"Boundary-Layer Receptivity Freestream Disturbances," Saric, Reed, Kerschen, *ARFM,*34 2002.

"CFD Validation Issues for Stability and Transition," Reed, Saric, *Invited Paper, ASME*, Montreal, Jul. 2002.

"Laminar Flow Control", Saric, Reed, *Invited Paper, AIAA Aerospace Sciences*, Jan. 2003.

"Stability of 3-D Boundary Layers," Saric, Reed, White, *ARFM* 35, 2003.

"CFD Validation Issues Boundary-Layer Stability," Reed, Saric, *Invited Paper,AIAA-2003-3441.*

"Numerical-Experimental Comparisons of Second-Mode Behavior for Blunted Cones," Lyttle, Reed, Shipyluk, Maslov, Buntin, Burov, Schneider, submitted to *AIAA Journal*.

"Toward Practical Laminar Flow Control-Remaining Challenges," Saric, Reed *(Invited). AIAA Paper 2004-2311*

"Stability, Transition, and Control of 3-D Boundary Layers on Swept Wings," Saric, Reed, *(Invited)* IUTAM Symposium *One Hundred Years of Boundary Layer Research*, Göttingen, Germany, Aug. 2004

"Experimental/Computational Collaboration in the Understanding of Boundary Layer Transition," *(Invited)* Reed, Saric, 24th Congress *Int'l Council Aero. Sciences,* Yokohama, Japan, Sept. 2004

"Flight Testing of Laminar Flow Control in High-Speed Boundary Layers," Saric, Reed, Banks, *NATO-RTO-MP-AVT-111*, Oct. 2004.

"Design and testing of a 30-degree sweep laminar flow wing for a high-altitude long-endurance aircraft," Solomon, Drake, Reed, Saric, *NATO-RTO-MP-AVT-111*, Oct. 2004.